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Calculated Experimental Evaluation of the Active Life of Microelectronic Devices for Space Purposes

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Abstract. The article presents a calculation-experimental estimate of the active lifetime (ALT) of microelectronic devices (MED) for space purposes. One of the structural elements that determines the ALT of the MED is an adhesive, which is used to mount the MED on the base of the main body. In the calculations, it is assumed that the degradation of the adhesive at elevated temperature is described by the Arrhenius equation. Three batches of prototypes of the MED with test structures were made, in which the mounting of the crystal of the test structure was carried out using the OTPK–P and VK–26M adhesives as a reference sample. Accelerated testing of test structures showed that the use of OTPK brand adhesives for mounting MEA could provide ALT of 15 years.

Keywords: adhesive, degradation, microelectronic device, lifetime, temperature

Introduction

A spacecraft is a complex technical system, which, during space flight, must fulfill its functions under conditions with destabilizing factors of the outer space: deep vacuum, large temperature difference, radiation, charged particle fluxes, etc. [1, 2]. Therefore, the onboard equipment (OE) of the spacecraft (SC) should have a mean time between failures of at least 130 thousand hours (15 years) and a storability of at least 25 years [3]. One of the possible ways to assess the active life of the equipment is to conduct accelerated testing of the devices that make it up, and, in particular, microelectronic devices (MED). In this regard, the calculation and experimental assessment of the active life of microelectronic devices for space applications is an extremely urgent task.

The purpose of this work is to develop an estimate of the active life of microelectronic devices that make up the OE of SC.

To achieve this goal it is necessary to solve the following tasks:

- choose the structural element of the MED, which determines the period of its active existence. According to [4], in some cases, this element is a structural material — adhesive used in the MED for attaching the crystal to either the base of the ceramic-metal casing or substrate. During the operation of the MED, chemically active compounds (for example, water, halogens, etc.) can be released from the adhesive, leading to its failure due to corrosion of aluminum coating. In addition, like any polymer material, the adhesive is subject to uncontrolled natural aging;

- choose a test method by which it is possible to obtain the data on the time of active existence of MED.

As a rule, acceleration of lengthy tests is achieved by increasing the temperature compared to the normal operation. In this case, the assumption is made that both at increased temperatures and under normal conditions, the same degradation processes are accelerated, leading to a failure of the device. The rate of degradation processes and failures of semiconductor devices, including MED, at an elevated temperature obeys the Arrhenius equation [5, 6], which allows linear extrapolation of test results from high temperatures to normal MED operating conditions.

For the MED to function, the adhesive must have a specific volumetric electrical resistance of no less than 10^{14} Ohm · cm and adhesion strength at separation of at least 2.0 MPa in the range of operating temperatures [7]. Degradation processes in the MED adhesion joint occur both during its functioning and downtime, and are manifested either in the loss of adhesive or insulating properties, or both of them. As a rule, the manifestation of the loss of adhesive properties in polymer coatings is due to the breaking of chemical bonds in the organic material and adhesive bonds with the substrate and the crystal of the device [8]. The emergence of currents leaks through the adhesive joint is the result of breaking bonds in the polymer matrix of the material with the formation of uncompensated valencies.

For mounting the MED crystal on the base of the metal ceramic casing, a one-component phenol-rubber adhesive VK–26M is used. It completely wets the bonded surfaces of the MED crystal and the ceramic base of the body, ensuring the formation of joints with a minimum thickness of the adhesive joint. The small thickness of the adhesive joint allows avoiding the destruction of adhesive joints due to internal stresses in the adhesive joint caused by the difference in coefficients of linear thermal expansion (CTE) of the materials and the adhesive. According to the authors of [9], after it is cured at a temperature of 523 K for at least 3 hours, it practically does not emit products capable of condensation, ensuring a minimum content of water vapor (up to 0.5% vol.) in the casing of the device with the adhesive connection.

It is known that not all MED elements withstand the temperature of 503–523 K during the curing of the adhesive. We also consider a one-component, heat-conducting, low gas emission, epoxy adhesive of the OTPK-P brand developed at the Kompozit JSC, which has high electrical insulation characteristics and a curing mode of 1 hour at 393 K or 2 hours at 423 K [10].

To conduct accelerated tests, a test structure was developed, which is a KDB – 7.5 <100> silicon crystal measuring 5.1 × 5.1 mm in size, coated with thermal oxide 0.5–0.6 μm thick, on which aluminum strips of various widths: 8, 16 and 24 microns are formed. The metallization thickness is 1 μm. The size of the contact pads of the strips is 120 × 100 microns. Aluminum wire outlets 30 μm in diameter was welded to them by the method of ultrasonic welding. Figure 1 shows a silicon wafer with a diameter of 76 mm with test structures. The total number of test structures on the plate was 88.

For testing, twelve samples of crystals of the test structure were made, the installation of which on the ceramic base of the H14.42–1B body was carried out using the VK-26M adhesive and two modified adhesives

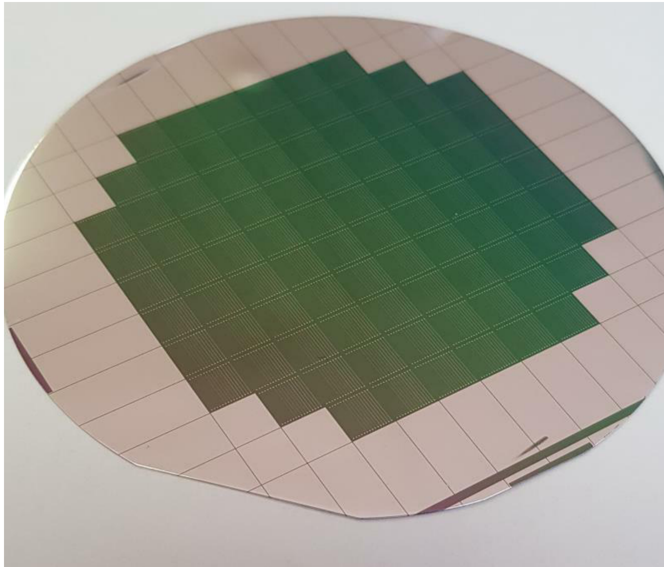

Fig. 1. Appearance of a silicon wafer with test structures

of the OTPK-P brand. Five samples used the OTPK– 5–C adhesive, and four used the OTPK– ED–3 adhesive. Three samples in which the VK–26M adhesive was used were comparison samples. After mounting the crystal, the case was sealed using the existing technology.

The calculation of the accelerated testing duration to confirm the active life of 15 years was carried out according to the technique presented in [11]. The mean activation energies of the failure process are taken from the Table 1 [11].

The activation energy of the failure process was selected based on the geometric dimensions of the gate of the CMOS IC transistor installed in the N14.42–1V casing. The gate size of the CMOS IC transistor is more than 1 μm. Therefore, the calculations used the data for the CMOS row ≥ 1.

According to [12], adhesive joints made with the VK-26M adhesive can withstand temperatures of 523 K for 500 hours, and temperatures of 573 K for 100 hours. The OTPK–P adhesives should have temperature stability no worse than the VK–26M adhesive. Therefore, the temperature of accelerated tests was taken equal to 473 K.

The calculation of the accelerated short-term (ASTT) and long-term (ALTT) failure tests at a temperature of 473 K was carried out using the following data:

- the value of power dissipation P_{dis} = 1.5 W;
- thermal resistance of the crystal – case R_{cr-cas} = 20°C/W;
- test temperature (ambient) T_{amb} = 100° C.

The value of the temperature of the crystal T_{cr} when testing at a temperature T_{amb} is determined, according to [11], by the formula:

$$T_{crSTT} = T_{crLTT} = T_{amb} + R_{cr-cas} \times P_{dis} \quad (1)$$

where: R_{cr-cas} is the crystal–casing thermal resistance ⁰C/W;
P_{dis} *is* the dissipation power in the forced mode, W;
T_{amb} *is* the ambient temperature in the forced mode, K.

Table 1. The activation energy values of the failure process for groups of integrated circuits at various temperatures of the crystal[11].

Integrated circuit group	The value of the generalized activation energy at different temperatures of the crystal (transition), eV			
	E_{a1}	E_{a2}	E_{a3}	E_{a4}
	25 - 70 ⁰C	71 - 150 ⁰C	151 - 200 ⁰C	201 - 250 ⁰C
Bipolar digital TTL, ECL	0.3	0.4	0.5	0.6
Bipolar digital TTL–S on p–MOS structures	0.3	0.5	0.6	0.7
Bipolar digital n–MOS structures, CCD	0.35	0.55	0.65	0.75
Bipolar Digital I^2L	0.4	0.6	0.7	0.8
CMOS ≥ 1.0 μm	0.45	0.65	0.8	0.9
CMOS 1.0–0.5 μm	0.55	0.75	–	–
CMOS 0.5–0.09 μm	0.6	0.8	–	–
Analog	0.45	0.65	0.8	0.9

where: TTL is transistor–transistor logic; ECL is emitter-coupled logic; TTL–S is transistor–transistor logic with Schottky diodes; CCD is device with charge coupling; I^2L is integral injection logic; n– and p – MOS are metal–oxide semiconductor structure with n and p type channels; CMOS is complementary metal-oxide semiconductor.

Substituting the numerical values in the formula (1), we obtained the value of the crystal temperature in the normal mode:

$$T_{STT} = T_{LTT} = 100\,°\text{C} + 1.5W \times 20°C/W = 130°\text{C}$$

The temperature of the crystal T_{cr} during the accelerated (forced) tests at $T_{amb.f}$=473 K was determined by the formula:

$$\text{T}_{\text{crASTT}} = \text{T}_{\text{crALTT}} = \text{T}_{\text{amb.f}} + \text{R}_{\text{cr-cas}} \times \text{P}_{\text{dis}} \quad (2)$$

where: $R_{cr\text{-}cas}$ is the crystal–casing thermal resistance ⁰C/W;

P_{dis} is the dissipation power in the forced mode, W;

$T_{amb.f}$ is the ambient temperature in the forced mode, K⁰C.

Substituting the numerical values in the formula (2), we obtained the value of the crystal temperature in the forced mode:

$$\text{T}_{\text{cr}ASTT} = \text{T}_{\text{cr}ALTT} = 200\,°\text{C} + 1{,}5W \times 20\,°\text{C}/W = 230\,°\text{C}$$

The activation energy of the failure process was selected based on the Table 1 data for CMOS≥ 1.0 μm.

In accordance with [11], the value of the acceleration coefficients for the long-term and short-term testing is determined by the formula:

$$\text{C}_{\text{ASTT}} = \text{C}_{\text{ALTT}} = \exp\left[\frac{\text{E}_\text{a}}{\text{k}} \times \left(\frac{1}{\text{T}_{\text{cr}}+273} - \frac{1}{\text{T}_{\text{cr.f}}+273}\right)\right] \quad (3)$$

where: E_a is the activation energy of the failure mechanisms, eV;

k is the Boltzmann constant, $8.6 \cdot 10^{-5}$, eV/K;

T_{cr} is the temperature of the crystal (transition) in the normal mode, °C;

$T_{cr.f}$ is the temperature of the crystal (transition) in the forced mode, °C;

Since T_{cr} and $T_{cr.f}$ lie in different temperature ranges (for which different values of activation energy are shown in Table 1), the total acceleration coefficient is equal to the product of acceleration coefficients calculated for each temperature range according to the formula (3).

Substituting the numerical values for the above temperature ranges, we obtained the numerical values of the acceleration coefficients K_1, K_2, and K_3, respectively, equal to 2.489, 10.227, and 3.525.

Then according to [11], the total acceleration coefficient is equal to:

$$\text{К}_\text{a} = \text{К}_1 \times \text{К}_2 \times \text{К}_3 \quad (4)$$

$$\text{К}_\text{a} = 2{,}489 \times 10{,}227 \times 3{,}525 = 89{,}729.$$

The duration of accelerated short-term reliability tests was determined by the formula:

$$\text{t}_{\text{ASTT}} = \frac{\text{t}_\text{T}}{\text{К}_\text{A}}, \quad (5)$$

where: t_T = 1000 h is the duration of long-term reliability tests (LTT);

K_{ASTT} is the acceleration coefficient for the accelerated short-term reliability tests [11].

Substituting the values of the duration of the long-term reliability test and the acceleration coefficient for the accelerated short-term reliability test in the formula (5), we obtain:

$$t_{\text{ASTT}} = \frac{t_\text{T}}{\text{К}_\text{A}} = \frac{1000}{89.729} = 11.15\text{ h}.$$

The duration of accelerated long-term reliability tests is determined by the formula:

$$\text{t}_{\text{ALTT}} = \frac{\text{t}_{\text{LTT}} - \text{t}_\text{T}}{\text{К}_\text{A}}, \quad (6)$$

where: t_{LTT} = 131400*h* is the duration of long-term reliability tests;

t_T is the LTT duration;

K_{ALTT} is the acceleration coefficient for the accelerated short-term reliability tests.

Substituting the numerical values in the formula (6), we obtain:

$$\text{t}_{\text{ALTT}} = \frac{\text{t}_{\text{LTT}} - \text{t}_\text{T}}{\text{К}_\text{A}} = \frac{131400 - 1000}{89.729} = \frac{130400}{89{,}729} = 1453{,}27\text{ h}.$$

Then the total time for accelerated testing, according to [11], is:

$$\text{t}_{\text{AT}} = \text{t}_{\text{ASTT}} + \text{t}_{\text{ALTT}} = 11.15 + 1453.27 = 1464.42 \approx 1465\text{ h}.$$

Before testing at elevated temperatures, all elements of the test structures were measured for their resistance R_{0i}. The measurements were carried out using the 4-probe method using a GOM–802 digital milliometer.

The test structures were exposed at a temperature of 473 K in a vertical heat chamber PV–212. Every 100 hours, the test structures were removed from the chamber, cooled to room temperature for 30 to 40 minutes. After that, the resistance of the elements of the test structures was measured using the 4-probe method. The first measurement was carried out after 48 hours in the chamber.

The results of changes in the resistances of the elements of the test structure are presented in the graphs plotted on a semi-logarithmic scale, where the X axis is the heat exposure time τ, in hours, on a logarithmic scale, the Y axis is $R_{rel.i}$, the relative change in the resistance value of the i element in%, calculated by the formula:

$$R_{rel.i} = \frac{R_i - R_{0i}}{R_{0i}} \times 100\% \quad (7)$$

where: i is the number of the element of the test structure, i varies from 1 to 9;

$R_{0\,i}$ is the resistance value of the i element before the start of testing.

Figures 2–4 show the results of testing test structures at a temperature of 473 K for 1788 hours. Figures 2 and 3 show the results of changes in the resistance of the elements of the test structures, the crystals of which were mounted with the OTPK–ED–3 (structure No. 1) and OTPK–5–C (structure No. 6) adhesives.

Similar dependences were obtained for the seven remaining samples with the OTPK–P adhesives. As can be seen from the graphs presented, at the initial stage of the test (up to 248 hours), a decrease in the resistance of the resistive elements of the test structures from 5 to 8% is observed, then with a further continuation of the test, a monotonic increase in the resistance of the elements from 10 to 40% is observed (up to a test duration of 748 hours), then follows the same decrease in resistance (up to a test duration of 1088 hours) from 15 to 45%. With continued testing up to 1788 hours, a gradual decrease in the resistance of the elements of the test structures was observed.

The same dependences were obtained on comparison samples in which the crystals of test structures were mounted using the VK–26M adhesive. Data on the accelerated testing of the test structure No. 2, in which the VK-26M adhesive was used, is presented in Figure 4.

As a result of the accelerated testing, all the elements of the test structures showed a decrease in the resistance of resistive elements by 10–15% compared to the initial resistance and none of the elements failed during the testing. Thus, the test structures with both OTPK–P adhesives and VK–26M adhesive passed the accelerated tests at 473 K for 1465 h, which should correspond, according to the above calculations, to 15 years.

The decrease in the resistance of the resistive elements of the test structures during the initial testing is due to annealing of defects in the aluminum film produced by ion-plasma spraying. In addition, it is known that the films obtained are polycrystalline in structure, while the crystal grains are coated with a

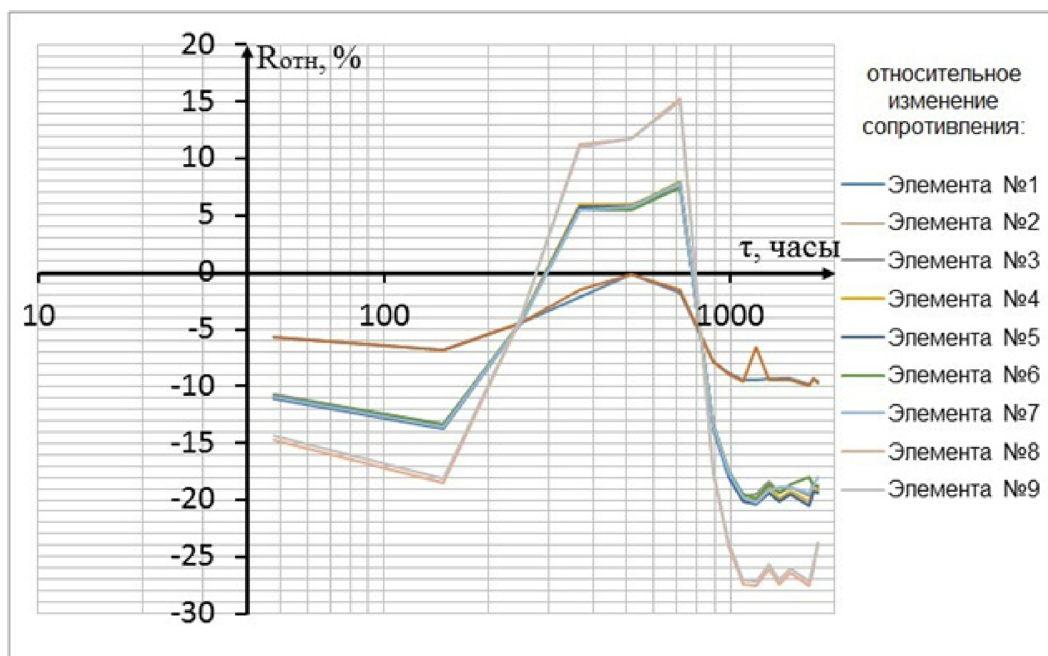

Fig. 2. Relative change in the resistance of elements of the test structure No. 1 with the OTPK–ED-3 adhesive during the accelerated tests at a temperature of 473 K: No. 1, No. 2 — changes in R_{rel} of resistive elements with a track width of 8 μm; No. 3 – No. 7 — changes in R_{rel} of resistive elements with a track width of 16 μm; No. 8, No. 9 — changes in R_{rel} of resistive elements with a track width of 24 μm.

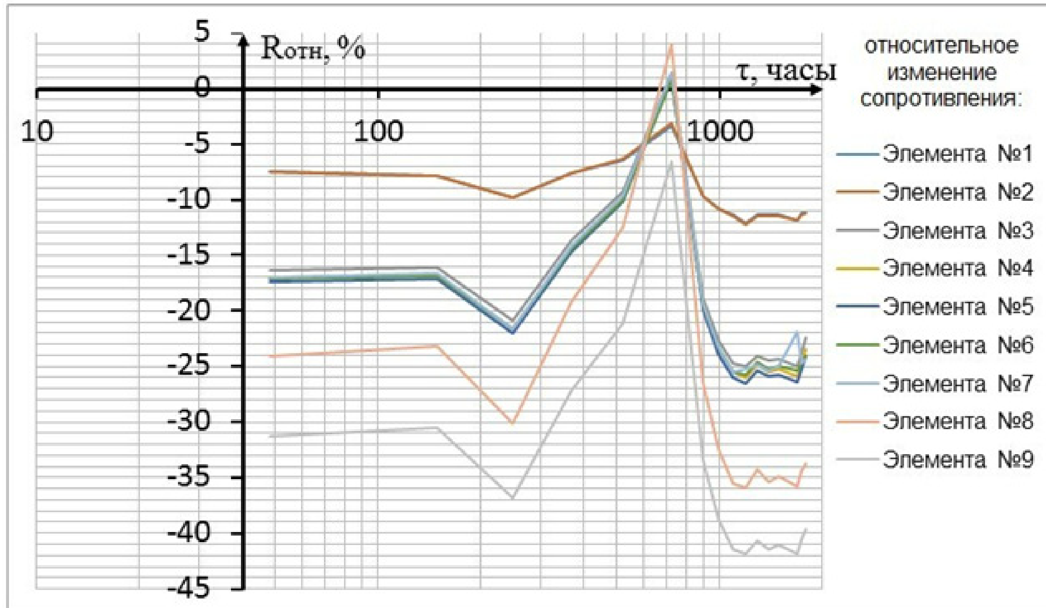

Fig. 3. Relative change in the resistance of elements of the test structure No. 6 with the OTPK-5-S adhesive during the accelerated tests at a temperature of 473 K: No. 1, No. 2 — changes in R_{rel} of resistive elements with a track width of 8 μm; No. 3 – No. 7 — changes in R_{rel} of resistive elements with a track width of 16 μm; No. 8, No. 9 — changes in R_{rel} of resistive elements with a track width of 24 μm.

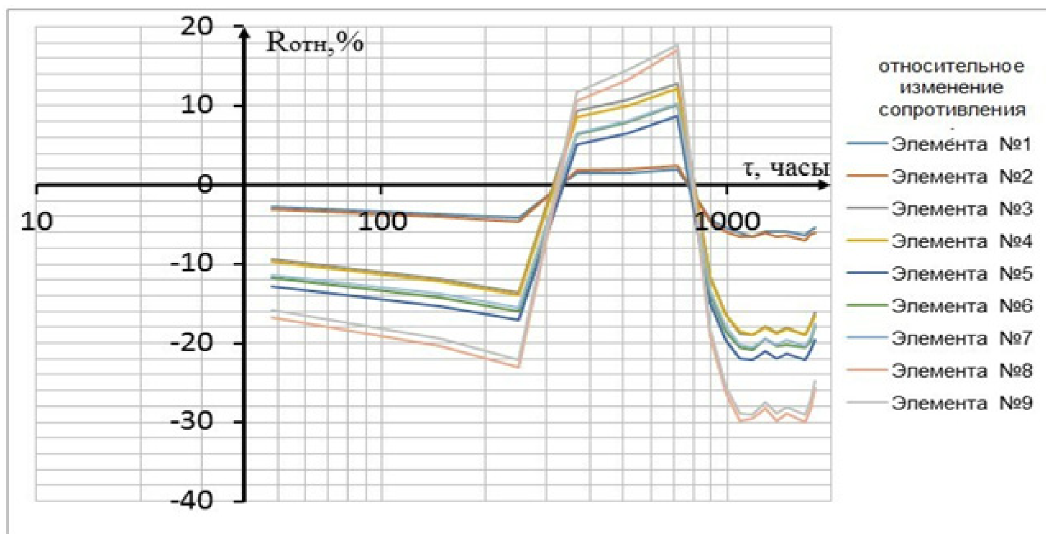

Fig. 4. Relative change in the resistance of elements of the test structure No. 2 with the VK-26M adhesive during the accelerated tests at a temperature of 473 K: No. 1, No. 2 — changes in R_{rel} of resistive elements with a track width of 8 μm; No. 3 – No. 7 — changes in R_{rel} of resistive elements with a track width of 16 μm; No. 8, No. 9 — changes in R_{rel} of resistive elements with a track width of 24 μm.

natural oxide with an amorphous structure [13]. The oxide thickness is about 6 nm and it is the ɣ – Al_2O_3 phase [13]. During the test (during heating), a phase transition occurs - the transition of the amorphous ɣ–Al_2O_3 phase to the crystalline phase in the form of α–Al_2O_3. When an amorphous modification transforms into a crystalline one on the surface of alumina particles, chemically active centers disappear, which may be sites with structural defects or weak Al – O chemical bonds. We observed this phenomenon with a test duration of more than 248 hours — an increase in the resistance of the resistive elements of the test structures as the amorphous phase transitions to crystalline. As is known, the transition of the amorphous phase to the crystalline phase will be accompanied by a

change in volume due to a denser packing of atoms, and an oxide film will crack [13]. In addition to the annealing of defects in the aluminum film during the test, its crystals will grow, moreover, the growth occurs due to a decrease in the fraction of the small ones. Changing the size of the crystals should lead to a decrease in the resistance of the aluminum film, which is observed with a test duration of more than 1000 hours Most likely, the transition of the amorphous phase to the crystalline phase ends at the test site from 700 to 1000 h, the growth process begins to play an increasingly important role, as a result of which a monotonic decrease in the resistance of the resistive elements of the test structures is observed.

As a result of accelerated testing of test structures with crystals, the installation of which was carried out using the OTPK– ED–3 and OTPK–5–C adhesives, it was found:

- the use of these adhesives for gluing microelectronic devices can provide an active life cycle of 15 years. However, the obtained calculations and experimental data require additional verification and confirmation regarding the mechanical strength of the adhesive joints;

– the variance in the tested parameter, the resistance of the resistive element made of aluminum film, during the test does not exceed 10 to 15%.

References

1. Model' kosmosa: nauchno–informatsionnoe izdanie [Model of the cosmos: scientific and informational publication]. In 2 volumes. Ed. by Panasyuk M.I., Novikov L.S. Vol. 1. Fizicheskie usloviya v kosmicheskom prostranstve [Physical conditions in outer space]. Moscow, 2007, KDU 872 p. (in Russian)
2. Model' kosmosa: nauchno–informatsionnoe izdanie [Model of the cosmos: scientific and informational publication]. In 2 volumes. Ed. by Panasyuk M.I., Novikov L.S. Vol. 1. Vozdeystvie kosmicheskoy sredy na materialy i oborudovanie kosmicheskikh apparatov [The impact of the space environment on the materials and equipment of spacecraft]. Moscow, 2007, KDU 1145 p. (in Russian)
3. Sevastyanov N.N., Andreev A.I., Osnovy upravleniya nadezhnost'yu kosmicheskikh apparatov s dlitel'nymi srokami ekspluatatsii [Fundamentals of the Reliability Control of Spacecraft with Long Service Life], Tomsk, TSU Publishing House, 2015, p. 266. (in Russian)
4. Kharlamov M.S., Zhukov A.A., Didyk P.I., Bezmen V.P. Degradatsionnye protsessy ustroystv mikrosistemnoy tekhniki [Degradation Processes in Microsystem Technology]. Raketno–kosmicheskoe priborostroenie i informatsionnye sistemy [Rocket-Space Device Engineering and Information Systems], 2018, Vol.5, No. 3, pp. 87–96. (in Russian)
5. Strogonov A.V. Otsenka dolgovechnosti BIS po rezul'tatam uskorennykh ispytaniy, [Assessment of the durability of LSI based on the results of accelerated tests]. Tekhnologii elektronnoy promyshlennosti [Electronic industry technology]. 2007, No. 3, pp. 10–16. (in Russian)
6. Kolpakov A. O termotsiklakh i termotsiklirovanii [On thermocycles and thermocycling]. Silovaya elektronika [Power electronics]. 2006, No. 2, pp. 6–11. (in Russian)
7. Gora Z.Yu. Tekhnologiya mikroelektronnykh ustroystv: Spravochnik [Technology of microelectronic devices: a Handbook]. Moscow, Radio i svyaz', 1991, 528 p. (in Russian)
8. Voronin I.V., Kondrashov E.K. Dolgovechnost' adgezionnykh svyazey polimernykh pokrytiy [Durability of adhesive bonds of polymeric coatings]. Available at: www.viam.com/public (in Russian)
9. Lukina N.F., Petrova A.P. Svoystva i primenenie kleev v pribornoy tekhnike [Properties and use of adhesives in the instrument technology]. Klei. Germetiki. Tekhnologii [Adhesives. Sealants. Technology]. 2005, No. 11, pp. 11–16. (in Russian)
10. Gladkikh S., Stepanov A., Antipin S. Teploprovodyashchie elektroizolyatsionnye klei dlya sborki izdeliy mikroelektroniki [Thermally conductive electrical adhesives for the assembly of microelectronic products]. Pechatnyy montazh [Printed circuitry], 2017, No. 3, pp. 183–187. (in Russian)
11. GOST R 57394-2017 Metody uskorennykh ispytaniy na bezotkaznost' [Methods of accelerated tests for reliability]. (in Russian)
12. Kalisevich V.P., Antipova T.I., Petrova A.P. Opyt primeneniya kleev pri izgotovlenii magnitoprovodov [Experience in the use of adhesives in the manufacture of magnetic circuits]. Available at: www.viam.com/public. (in Russian)
13. Zenin V.V., Spiridonov B.A., Zemlyansky A.I., Bokarev D.I. Korrozionnaya stoykost' alyuminievoy metallizatsii kristallov korpusov poluprovodnikovykh izdeliy [Corrosion resistance of aluminum metallization of semiconductor products case crystals]. Vestnik Voronezhskogo gosudarstvennogo tekhnicheskogo universiteta [Bulletin of the Voronezh State Technical University], 2015, vol.11, No.6, pp. 34–37. (in Russian)